

**UNITED STATES AIR FORCE
RESEARCH LABORATORY**

**EFFECTS OF CONTINUOUS AND STROBING
LASER GLARE ON PERFORMANCE IN A
VISUALLY SIMULATED FLIGHT TASK**

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Strobing laser glare may present a threat to aircrew. In addition to obscuring the visibility of instruments and terrain (as continuous exposures can), strobing exposures could potentially impede visual motion processing. This report describes a study in which a low-cost, medium-fidelity virtual cockpit environment was used to measure the effects of strobing vs. continuous laser exposure on performance in a visual flight task. Results suggest that strobing laser glare poses a legitimate threat to visual orientation control, that this threat might rival or eclipse that posed by continuous laser sources, and that further examination of the threat is needed.				
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CONTENTS

INTRODUCTION	1
BACKGROUND	1
DESIGN AND METHOD	2
Subjects	3
Displays and apparatus	3
Experimental design	5
Laser, steering optics, and safety devices	5
Laser exposures and hazard calculations	6
The attitude regulation task: dynamics, procedure, and measures	6
RESULTS AND DISCUSSION	8
RMS attitude measures	8
Mean absolute-value measures	9
Crashes	10
Plotting deterioration in attitude control following laser onset	10
Discussion	11
CONCLUSION	13
REFERENCES	13
APPENDIX: Calculating the forcing functions and the instability parameter	15

FIGURES

1. Configuration of the simulator	3
2. The simulated HUD attitude instrument	4
3. Attitude control performance: pitch and roll RMS	8
4. Attitude control performance: mean error absolute values	9
5. A time history of stick corrections, plotted throughout one trial	10
6. Pitch control performance, plotted throughout the same trial	11

INTRODUCTION

Exposure to laser glare is potentially disorienting and destructive to aircrew operating in the field. Even at low power levels, cockpit glare from an external laser source appears capable of degrading performance on dynamic flight tasks, which require visual processing of moving stimuli. It is possible that this threat may be increased by strobing or “chopping” the laser exposure over time, which could alter viewers’ contrast sensitivity, motion perception, and visual search processing, relative to performance obtained under conditions of continuous illumination. The threat posed by strobing lasers to the performance of dynamic visual tasks has not yet been characterized fully, however; laboratory and field studies to date have generally used continuous glare sources, or static visual tasks¹. The research described in this paper combined laser technology with visual simulation to measure the effects of low-level laser glare on the performance of visual flight tasks in strobing vs. continuous exposure conditions.

The study was conceived and supported as an Entrepreneur Research project by the Air Force Research Laboratory. Within the scope of the project, it was possible to construct the virtual cockpit environment incorporating a simulated laser threat, to design and implement a virtual flight task and performance measures, and to conduct a pilot experiment comparing different laser exposure conditions.

BACKGROUND

Light traveling from a luminous or reflective source to the observer’s retina can be scattered both outside and within the eye. This stray-light, known as glare, can degrade the retinal image and interfere with performance in a variety of visual tasks and conditions. Glare elevates discrimination thresholds throughout the human contrast sensitivity function (Finlay & Wilkinson, 1984). On the road, glare from oncoming headlights can impede motion perception and the detection and discrimination of objects (including vehicles) throughout the visual field. These effects may be underestimated by standard visual performance tests (Attwood, 1979; Bichao, Yager, & Meng, 1995), particularly when observers have lens opacities (Anderson & Holliday, 1995).

The advent of mobile and relatively inexpensive laser devices in both military and civilian settings has heightened the potential visual performance threat from glare, because lasers can propagate an intense stream of energy over long distances with relatively little dispersion, compared to non-coherent light. Like broad-band light from headlights or the sun, lasers in the visible spectrum can impede visual performance in a number of ways even when the exposures are at low, non-lethal power levels. Lasers can induce temporary scotomas (regions of transient flashblindness in the visual field), where the acquisition of visual targets is impaired (Kosnik, 1995). Laser glare can impair speed and accuracy in visual search tasks, and these effects are aggravated when an aircraft windscreen is interposed between the viewer and the target scene (D’Andrea & Knepton, 1989; Reddix et al., 1990, 1998). In addition, continuous laser exposure has been shown to impede manual tracking of visually pursued targets, both in the laboratory and in homologous field tests incorporating an actual military targeting device (Stamper, Lund, Molchanov, & Stuck, 1997).

¹ Stamper et al. (1997), for example, combined a dynamic tracking task with continuous 3-s laser exposures, whereas Reddix et al. (1998) used chopped laser light in a visual search task incorporating a static stimulus array.

An additional factor that could influence the visual performance threat from laser glare is temporal modulation (strobing) of the beam by chopping or pulsing the source. Since a strobing glare source masks (and reveals) the scene intermittently, this might be expected to interfere with the detection and interpretation of visual motion in some conditions. In non-laser environments, temporal modulation of the scene illumination has been found to affect visual performance differently from continuous illumination. Amblard et al. (1985), for example, compared the effects of stroboscopic vs. continuous background illumination on the visual regulation of stance, and determined that separate visual orientation mechanisms operate in the respective conditions. They proposed that a dynamic visual orientation mechanism operates when the observer views continuous motion or stroboscopic displays with frequent frame rates, and that an alternative orientation mechanism, operating on static visual cues, comes into play at low stroboscopic frequencies. According to this model, the dynamic orientation mechanism supports whole-body stabilization and is vulnerable to strobing illumination; this finding is clearly relevant to visual spatial orientation and vehicle control.

Intermittent illumination has also been found to disrupt human performance with actual instruments and control interfaces. Kappe (1997) demonstrated that reducing a virtual display's update rate (which, like temporal modulation of background illumination, can weaken or eliminate the visual motion signal) can impede tracking of a remotely piloted vehicle. Zeiner and Brecher (1975) conducted an instrument monitoring task in which subjects were to report deflections of an indicator needle, and found that responses were slower in the presence of pulsed, strobing illumination. It should be noted that intermittent illumination can in some cases impair visual processing of a moving stimulus without rendering that stimulus invisible; consider, for example, the hypothetical task of negotiating a path through a crowded room (or trying to hit a tennis ball) under conditions of stroboscopic illumination.

The studies described above indicate that intraocular glare can impair visual performance, that lasers can amplify this threat and propagate it across long distances in the field, and that strobing illumination may interfere with dynamic visual processing. These various manifestations of the visual glare threat make it desirable to test the effects of strobing, low-power laser exposure on performance in dynamic visual flight tasks, because it seems clear that such exposures could present a non-trivial threat to aircrew operating in the field. This paper describes the first in a series of experiments designed to accomplish this in a simulated cockpit environment.

DESIGN AND METHOD

The experimental task was constructed to meet several criteria. First, it should approximate the human performance requirements underlying the perception and control of spatial orientation during flight; i.e. it should require attitude regulation over time. Second, the task should include a visual target or instrument that moves continuously (or at least updates at a high enough frequency to approximate visual motion). This enables testing the hypothesis that strobing laser exposure will disrupt visual motion processing to a disproportionate extent compared to continuous exposure at equivalent power levels. Last, we wished to display the orientation information in a configuration that resembled the primary flight display found in a real cockpit. These criteria were satisfied using a dual-axis control task incorporating a joystick and a simulated HUD (head-up display) attitude indicator adapted from an actual high-performance cockpit application.

Subjects. Four male volunteer subjects participated from the Air Force Research Laboratory, Brooks AFB. One subject was a former Air Force pilot and the remaining three had some experience flying visual flight simulators. All subjects had normal or corrected vision with at least 20/30 acuity, and were experienced with the attitude maintenance task, having performed it in several earlier studies and in piloting and training sessions for this experiment. The experiment was completed in one session, which included 21 trials and required approximately one half-hour. The voluntary, informed consent of all subjects was obtained as required by Air Force Regulation 169-3.

Displays and apparatus. Displays were generated using a Silicon Graphics Crimson workstation with a Reality Engine graphics processor. The display was presented on a Seos Midas collimated system with 1280 x 1024-pixel resolution, viewed in a sound-attenuated chamber. The frame update rate ranged from 16 to 18 frames/s. The overall field of view was 44 deg (horizontal) x 27 deg (vertical). The video display monitor was mounted in the ceiling of the chamber and faced downward into a beam-splitter², which steered the out-the-window display rearward, away from the viewer and toward a spherical mirror (Figure 1). This reflected, collimated image then projected forward through the beam splitter towards the viewing position.

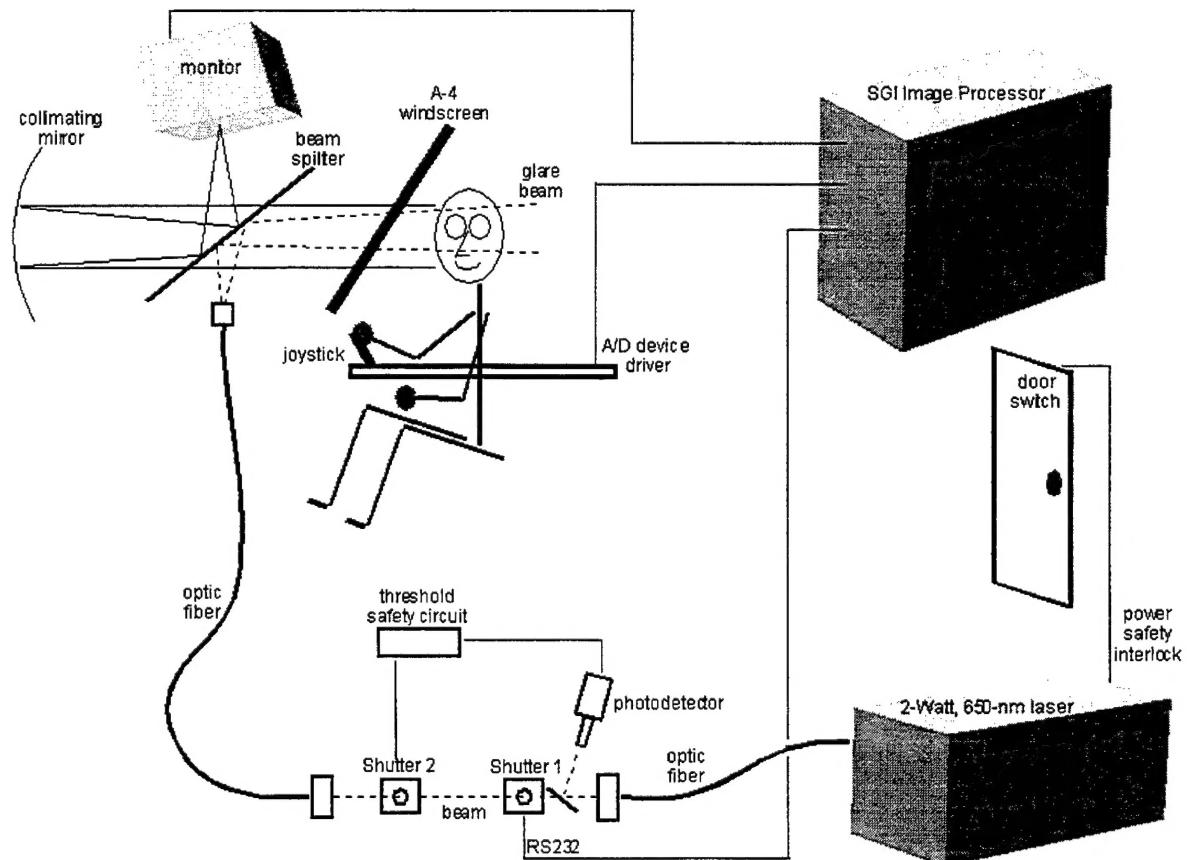


Figure 1. Configuration of the simulator (schematic section view).

² As shown in Figure 1 and in the "Laser, steering optics, and safety devices" section, the beam-splitter was used also to steer the laser beam.

The instrument for the experimental task was a simplified rendering of a 1787b HUD attitude indicator as used in the T-38 aircraft (Figure 2). The symbol strokes were green, to approximate the hue of actual HUD systems. Symbols were drawn on a uniform blue-gray twilight background. Mean luminance levels for the HUD symbol and background were .28 ft-L and .15 ft-L, respectively. The control interface comprised a joystick and A-to-D driver.

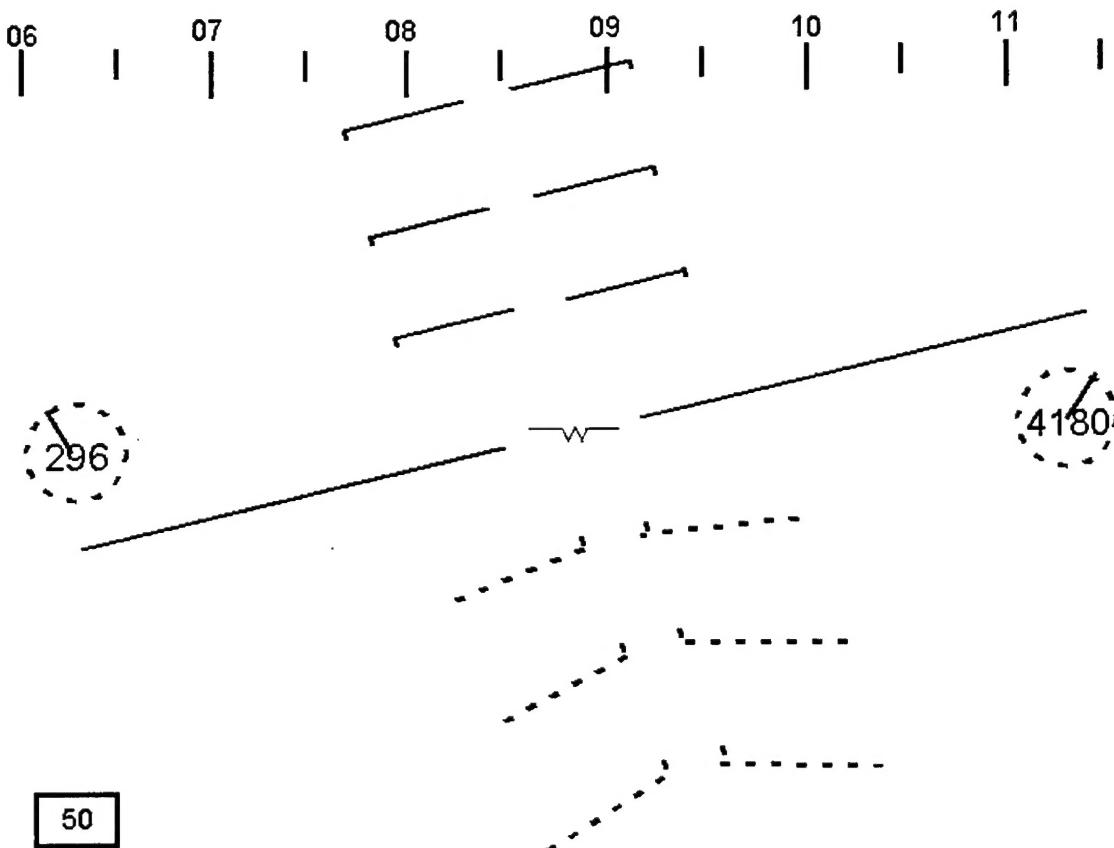


Figure 2. Simulated HUD attitude display.

The virtual HUD comprised a flight path marker, an artificial horizon, and a climb-dive ladder. The instrument configuration was “inside-out”, meaning that the flight path marker remained stationary in the center of the HUD and the horizon and climb-dive indicators (which represented the world’s frame of reference) rolled and scrolled around it. The artificial horizon subtended approximately 29 deg from side to side. Each rung on the climb-dive ladder represented 5 deg of vehicle pitch for indicated pitch angles up to ± 30 deg, and 10 deg of pitch for steeper indicated pitch angles. The dive marker rungs situated below the horizon comprised pairs of dashed line segments that flanked the vertical pitch meridian; these segments were angled upward in the middle with an acuteness that increased with the steepness of the indicated pitch attitude. The climb marker rungs situated above the horizon comprised pairs of solid segments also flanking the pitch meridian, but each pair was collinear and parallel with the

horizon. Hatch marks pointed downward from the outer ends of the climb indicators. The climb and dive marker rungs subtended approximately 11.4 deg from side to side. The HUD included digital gauges for heading, altitude, throttle, vertical velocity, and airspeed but these were not used in the experiment. A section of windscreens from an A-4 aircraft was suspended in the model cockpit to provide an optical scattering medium resembling those that aircrew might face in real-world operations. The distance separating the viewer from the windscreens was approximately 19.1 cm, measured along a ray pointing from the design eye point toward the center of the HUD instrument.

Experimental design. The experiment included three conditions, namely continuous exposure, chopped exposure, and no exposure. Each condition included seven trial repetitions. In each trial, attitude data were gathered during a period of laser exposure and during equivalent periods immediately preceding and following the exposure. Task performance was thus measured before the potential deleterious effect from the laser glare, during the glare exposure, and during the recovery following the glare. Pre-, during-, and post-exposure periods were assigned also in trials in the no-laser condition; this accommodated the measurement of baseline performance during three data periods equivalent to those used in the two laser conditions. Performance data were collected in the pitch and roll axes, and were analyzed according to a 3 (exposure conditions) * 3 (pre- vs. during- vs. post-exposure) repeated-measures design.

Laser, steering optics, and safety devices. The glare source was the end of an optic fiber whose image was superimposed on the visual display. The fiber conducted light from a 650-nm diode laser (AOC Medical Systems) whose output power was adjustable up to a maximum of 2.06 W. Two safety devices were included. The first comprised an interlock switch that cut power to the laser in response to opening the door of the simulation chamber, and the second device was a threshold surge detector, described below. Laser light was delivered via two segments of multi-mode optic fiber, which were linked in series via an optical system that monitored and controlled the beam (Figure 1). The numerical aperture of the fiber was .37 (yielding a maximum exit beam divergence of 43.4 deg) and its core diameter was 400 μ m. The first fiber segment led from the laser unit to the optical beam management system, which incorporated a power monitor and two Uniblitz T132 shutters. A positive lens was used to collimate the beam exiting the first fiber and direct it through a neutral-density filter, which was angled to redirect a small percentage of the beam to a photodetector. The photodetector output was delivered to a threshold safety circuit, which would close one of the shutters in the event of a surge in power. After passing through the ND filter for the power monitor circuit, the beam passed to the first shutter, which governed the time-course of the laser exposure. The experimental software delivered an RS232 signal to the first shutter; depending on the laser presentation condition and the time within each trial, this signal caused the shutter to remain open continuously, remain closed continuously, or chop the beam and deliver strobing illumination. The second shutter was placed after the first and closed in response to a trigger signal from the threshold safety circuit. After the second shutter, a second lens shrank the beam and directed it into the second fiber segment, which terminated in a mount situated beneath the beam splitter of the display system. The beam exited upward from the fiber mount and reflected off the lower face of the beam-splitter toward the viewer. The mount was positioned to superimpose the laser image on the center of the HUD instrument. The

path length from the fiber source to the viewing position was approximately 1.0 m, including a distance of approximately 30 cm from the terminal to the beam splitter and 70 cm from the beam splitter to the design eye point. A photodetector was placed immediately adjacent to the viewing position, to the left of the viewer's cheek, to calibrate and verify the irradiance reaching the viewer. Output from this detector was measured before each experimental session using a Newport 1835-C optical meter.

Laser exposures and hazard calculations. When the laser was operated at its full power of 2.06 W, the fiber terminal delivered 226 mW, the energy remnant following loss in the fiber and the beam management systems. The nominal ocular hazard distance associated with this fiber configuration was approximately 37 cm, assuming direct intrabeam viewing for 7 s. As Figure 1 illustrates, the 1-m path length from the fiber terminal to the viewer was much greater than this, and the viewing configuration, moreover, would have prevented even a willfully self-destructive individual from easily viewing the beam directly.

In the two laser conditions, there was one 7-s exposure in each trial. In the continuous-exposure trials, the irradiance was 20 $\mu\text{W}/\text{cm}^2$. In the chopped exposure conditions, the pulse repetition frequency was 8 Hz and the duty cycle was 50%. Chopped exposure trials were matched to the continuous exposure condition for total energy delivered per trial; peak irradiance was set to 40 $\mu\text{W}/\text{cm}^2$, given the 50% duty cycle.

per-trial exposures. Maximum permissible exposure (MPE) levels were calculated as specified by the American National Standards Institute (ANSI, 1993). The MPE for a continuous exposure lasting 7 s is 7.8 mJ/cm². Each continuous-exposure trial delivered 20 $\mu\text{W}/\text{cm}^2$ for 7 s, or .14 mJ/cm², which was 1.8 % of the MPE for a single exposure.

The MPE for one flash of a 7-s train of laser flashes with a repetition frequency of 8 Hz and a 50% duty cycle is 0.082 mJ/cm² or 82 $\mu\text{J}/\text{cm}^2$. Each strob ing trial delivered .14 mJ/cm² total energy and 2.5 $\mu\text{J}/\text{cm}^2$ per flash, which was 3.04 % of the MPE for a train of multiple flashes.

cumulative exposures per 24-hour period. Subjects' total laser exposure was calculated for each 24-hour period in which testing occurred. In order to provide an additional, extra-conservative safety margin, each subject's cumulative 24-hr laser exposure was treated as a single continuous exposure³ and this cumulative energy level was compared to 10 mJ/cm² (the MPE established for extended exposures between 10 s and 10,000 s).

Each subject viewed seven trials in the continuous condition and seven trials in the strob ing condition. Each trial in both conditions delivered .14 mJ/cm², so the total energy exposure for one day's session can be considered 1.96 mJ/cm² (1960 $\mu\text{J}/\text{cm}^2$), which would equal only 19.6% of the MPE corresponding to a continuous 98-s (i.e. [(7 trials +7 trials)*7 seconds]) exposure.

The attitude regulation task: dynamics, procedure, and performance measures. The subject's task was to use the joystick to maintain level pitch and bank orientation, as indicated on the virtual HUD, throughout each trial. The attitude was calculated for each display frame according to a first order model that integrated rates of change in the pitch and roll dimensions. The joystick modulated pitch- and roll rates of change in linear relation to the magnitude of stick movements

³ This cumulative exposure calculation is not required by ANSI or AFOSH standards.

in the forward-back and lateral directions, respectively. Pitch and roll rates were determined jointly by the position of the joystick and by the instantaneous value of two forcing functions, which were applied to the pitch and bank dynamics and fluctuated unpredictably over time.

The control task was designed after the model of Kenyon & Kneller (1993) in which the balancing, hovering, or steering human observer is the control element in a closed-loop system that may include variable stability parameters. The task included two elements to make it more challenging. First, the forcing functions added unpredictable error values (gusts) to the pitch and roll rates throughout each trial. Second, a weak instability parameter (λ) was included in the model, which amplified any attitude error in an accelerating manner. Combining unpredictable gusts with the instability parameter ensured that a stable attitude could not be maintained over time without continual correction inputs: If the subject neglected the task for a few seconds, the vehicle model would topple into a severe (crash) orientation. A description of the forcing functions and the instability parameter is found in the Appendix.

Each trial began with a “ready” message. The virtual HUD then appeared, superimposed on the uniform twilight background. The task ran for 40 s per trial. Trials from the three conditions were intermixed randomly in the presentation order. Subjects could not predict whether or when the laser exposure would occur in each trial. Each trial, including those in the baseline, no-laser condition, included a 7-s exposure period whose onset time was assigned randomly within a window extending from the time 10 s into the trial to the time 14 s before the end of the trial. This accommodated the collection of data during the exposure period, during a 7-s period immediately preceding the exposure period, and during a 7-s period immediately following it. The instantaneous attitude, the magnitude of the rotational disturbance, and the magnitude of the subject’s corrective stick input were recorded at each frame during these pre-, during-, and post-exposure periods. These time histories were recorded for both the pitch and roll dimensions.

Two performance measures were calculated from the attitude time histories in each data recording period. The first was the root-mean-square (RMS) attitude error calculated across all frames in the period. The second was the mean of the absolute values of the attitude errors (i.e. the angular distances from zero deg orientation in pitch and roll) recorded across all frames. The latter measure was employed to address the potential for spurious error values in the calculation of the RMS measure⁴. Both measures were calculated for the pitch and roll axes, in the pre-, during-, and post-exposure data periods.

The occurrence of extreme orientations (crashes) was recorded for each subject. A crash was defined as the occurrence of a pitch attitude steeper than $+60$ deg or a bank attitude steeper than ± 90 deg.

In selected trials, the time histories of attitude, rotational gusts, and stick inputs were plotted on superimposed curves, to map graphically the time course of a subject’s deteriorating performance in response to the onset of the laser within a single trial.

⁴ In the event the subject lost control, the vehicle model would stabilize itself in an upside-down orientation that fluctuated about the 180-deg roll and 0-deg pitch values. This would cause overestimates of the roll variation (since the local fluctuations around this orientation would register as wild swings between extreme rightward and extreme leftward roll values) and underestimates of the pitch variation (since the vehicle would home itself to zero-deg pitch without any help from the subject). While such control losses occurred only occasionally, they might have compromised the RMS figure’s validity.

RESULTS AND DISCUSSION

RMS attitude measures. Across-subject RMS error means are shown in Figure 3. The main effect

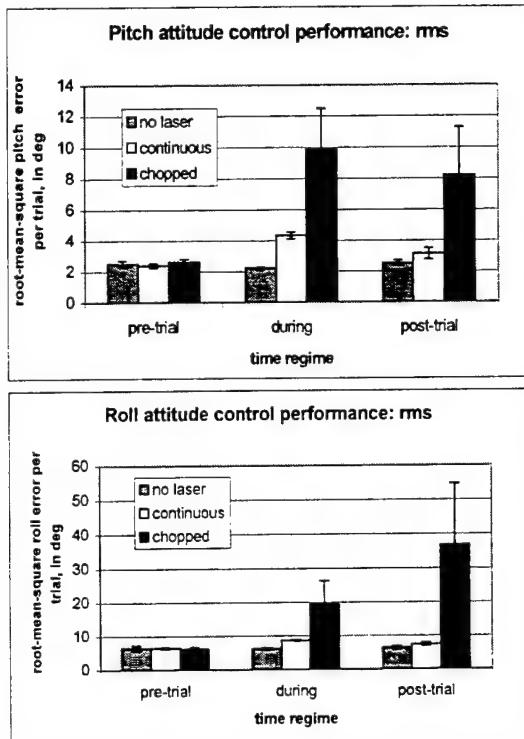


Figure 3. Attitude control performance as measured by pitch and roll RMS.

of laser condition on RMS error in the pitch axis missed statistical significance ($F(2,6) = 4.96, p = .054$). The main effect of time (pre-, during-, or post-exposure) was significant ($F(2,6) = 5.65, p < .05$), with the greatest errors occurring during laser exposure and with greater errors observed in the post-exposure period than in the baseline pre-exposure period. The interaction between condition and time was significant ($F(4,12) = 4.52, p < .02$), indicating that the deterioration of control performance during and following the exposure period depended on the presence and configuration of the laser. The greatest RMS pitch errors were observed in the "during" data period in the strobing laser condition. Pitch errors were less for continuous- than for strobing-exposure trials in this data period but still exceeded the baseline, no-laser error values; this distribution of means was observed also in the post-exposure period. As expected, pitch errors in the pre-exposure data period were similar across three conditions, and these values remained flat for the baseline no-laser condition throughout the remaining two data periods.

In the roll dimension, no significant main or interactive effects on RMS attitude error were identified. The strobing condition did exhibit the highest error values both during and after the exposure period. This performance gap between the strobing condition and the continuous and baseline conditions widened in the post-exposure recovery period. These changing differences among laser conditions in the different data periods manifested themselves in an interaction term that was not statistically reliable ($F(4,12), p = .062$), but suggested that strobing laser exposure does affect roll attitude control as it affected pitch control.

Mean absolute-value measures. As described in the footnote, the attitude RMS data might have been compromised in the occasional trials where subjects lost control. In these cases, the mean absolute value measure provided a more accurate representation of the attitude error. Across-subject means for this measure are shown in Figure 4. The distribution of means was similar to that observed with the RMS measures. In the pitch domain, a main effect of laser condition was observed ($F(2,6) = 5.22, p < .05$), with the greatest errors occurring in the strobing condition and with greater errors in the continuous condition than in the baseline no-laser condition. A main effect of time was identified ($F(2,6) = 6.74, p < .05$), with the greatest errors observed during laser exposure and with greater errors in the post-exposure period than in the baseline pre-exposure period. In contrast to the RMS analysis, the interaction between condition and time was significant ($F(4,12) = 5.18, p < .05$), indicating that the effect of time (pre-, during-, or post-exposure) on control performance depended on the presence and configuration of the laser.

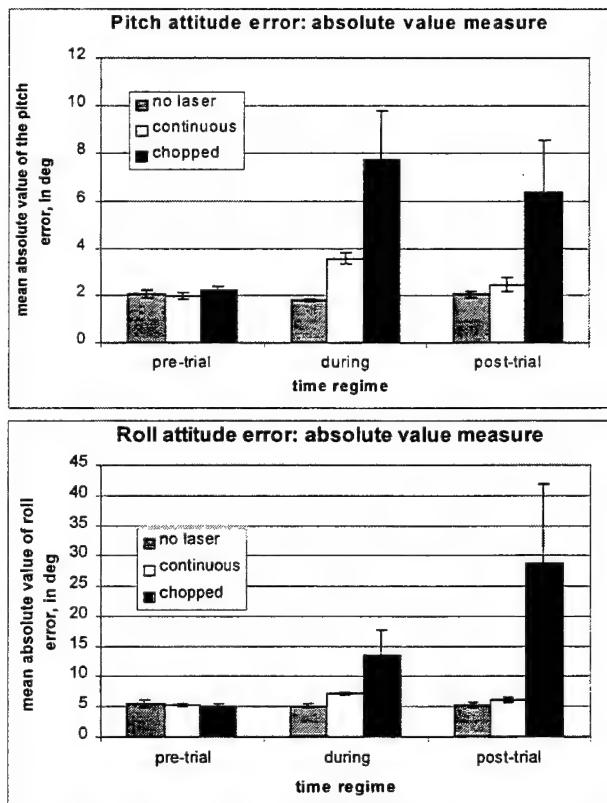


Figure 4. Attitude control performance as measured by the mean absolute value measures.

In the roll domain, the distribution of the mean error absolute values was consistent with this claim: While no significant main effect of condition or time was identified, the greatest errors (and hence the greatest control variability) were observed during and immediately after exposure to the strobing laser. As was the case with the RMS roll errors, the performance gap between the strobing condition and the remaining two conditions widened between the during- and post-exposure periods. A condition * time interaction ($F(4,12) = 3.44, p < .05$) reflected the differential effects of the laser conditions in the different measurement epochs.

Crashes. Two of the four subjects reached crash orientations on one or both control axes at least once. One subject crashed twice, in strobing trials on both occasions. The second subject crashed six times, again under strobing exposure conditions in all cases.

Plotting deterioration following laser onset. In selected trials, the time histories of attitude, rotational gusts, and stick inputs were plotted on superimposed curves, to map graphically the time course of a subject's deteriorating performance in response to the onset of the laser within a single trial. Figure 5 shows an example of a strobing exposure trial for which the time histories for rotational gusts and stick behavior in the pitch dimension have been superimposed. The laser onset, indicated by the white square wave, occurred approximately halfway through the trial. The curves indicate clearly that the amplitude of the subject's corrective stick inputs subsided quickly once the train of laser flashes began. Figure 6 depicts the dynamic effects on pitch orientation over time in the very same trial: Once the subject's active attitude regulation had died away, the vehicle slipped into a severe pitch orientation within a few seconds. The most extreme pitch orientation was recorded at the end of the laser exposure, at which time the subject began to initiate an attitude recovery.

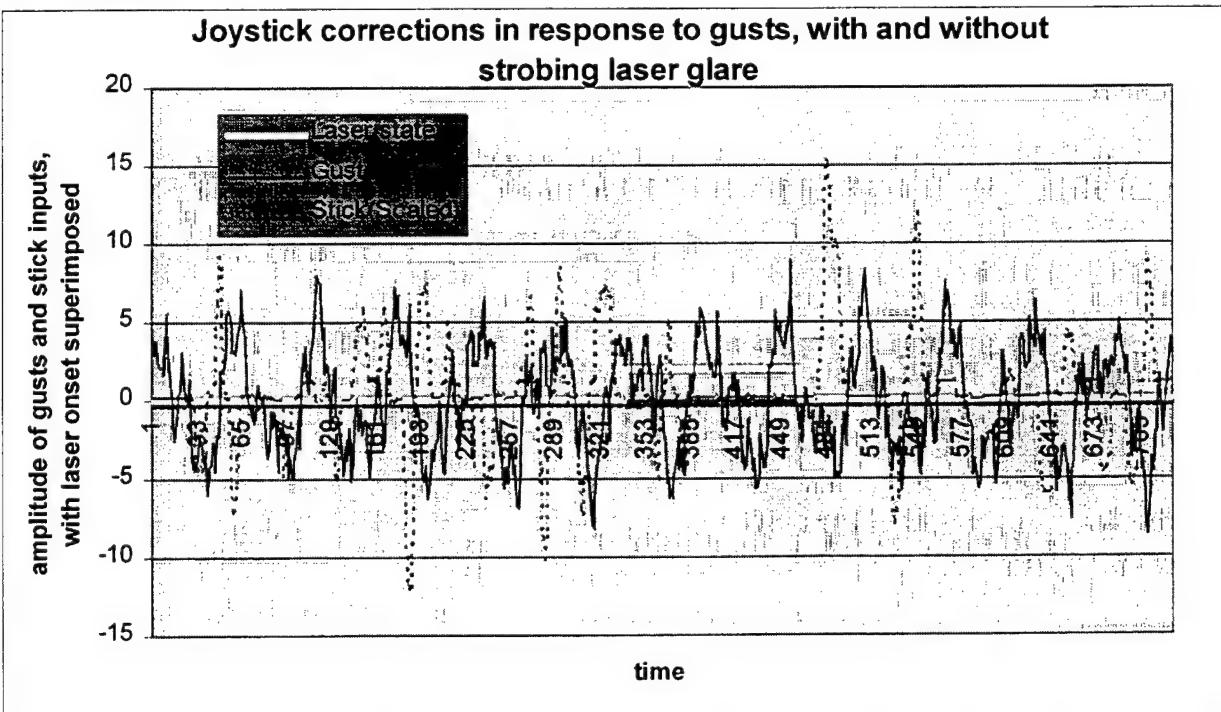


Figure 5. Time history of joystick corrections in response to simulated gusts. Control performance is depicted before, during, and after a strobing laser exposure.

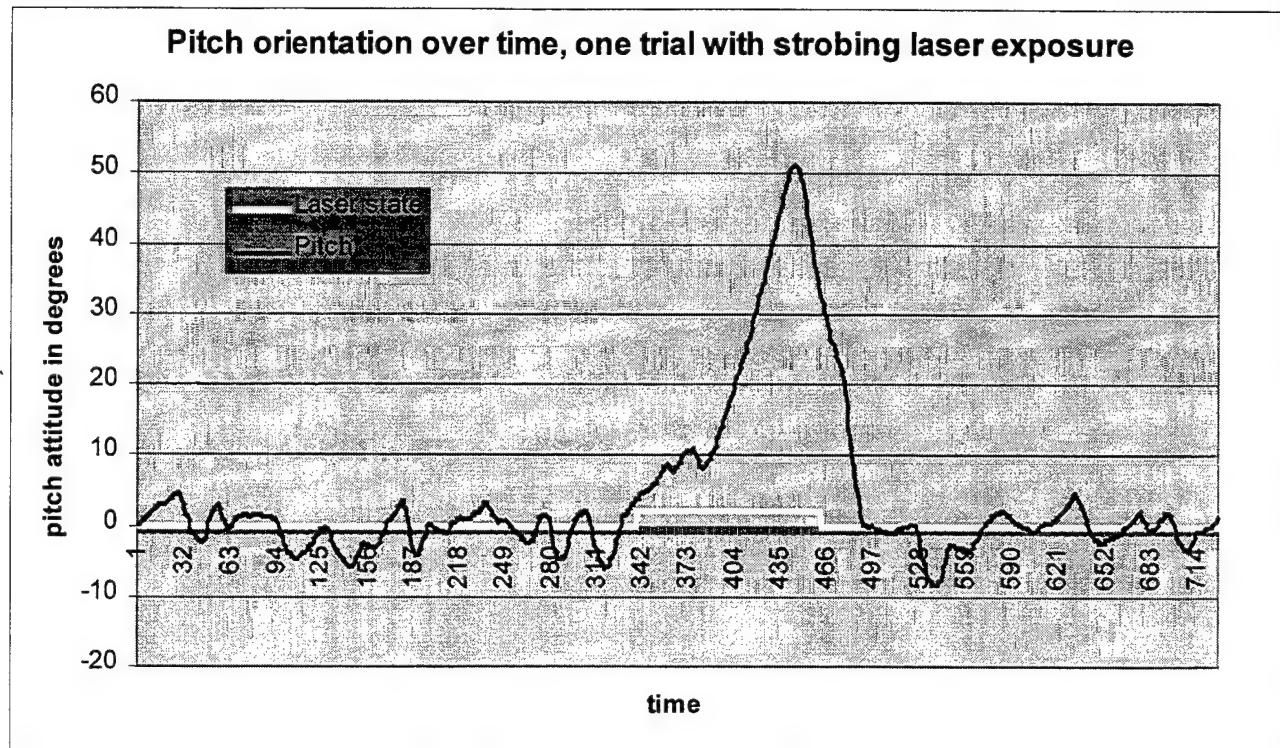


Figure 6. Time history of pitch attitude before, during, and after laser exposure in the same trial.

Discussion. It should be noted that these findings were not obtained with naïve subjects; all had some knowledge of the visual performance effects from laser glare and of the theoretical basis of the experiment. Since this knowledge might constitute experimental cueing, the findings need to be replicated with a larger group of subjects with no background knowledge or expectations. Granting this qualification and the small scale of this pilot study, we may consider the results, which suggest that strobing laser glare may pose a legitimate threat to visual orientation control and that this threat might rival or eclipse that posed by continuous laser sources.

The conditions including laser exposure, particularly the strobing condition, led to increased control errors relative to the baseline no-laser condition. Both the RMS and mean absolute-value measures indicated that strobing exposures were more disruptive than continuous exposures that were matched for cumulative energy delivery. As we see in Figures 3 and 4, moreover, orientation control performance appeared to be much more variable under strobing laser conditions, whereas performance could be mapped within a narrow window of variability under no-laser or continuous-laser conditions. Consistent with this, subjects allowed the vehicle to slip into extreme, “crash” orientations only under strobing exposure conditions.

Subjects’ qualitative descriptions also indicated an apparent increased vulnerability to glare in the strobing condition. The two subjects who experienced crashes remarked that in some of the glare trials “with the flashing light”, they simply lost track of the symbology and were unable to recover orientation until the exposure ended. One subject commented that in the continuous exposure trials, the glare field obscured the central part of the HUD, but he could nevertheless use the peripheral regions of the instrument, particularly the ends of the artificial horizon, throughout most of the exposure.

These data and the subjects' qualitative evaluations indicate that both laser conditions affected visual performance adversely, but not necessarily in the same way. It is notable that attitude errors and error variability were generally less in the continuous condition than in the strobing condition, and that error variability was generally comparable between the continuous and no-laser conditions. Exposure to continuous glare at this power level did create a virtual scotoma (an area of visual impairment within which a significant portion of the HUD instrument was washed out), but viewers could apparently process visual transformations occurring outside the scotoma using the remaining area of the instrument. Strobing illumination, by comparison, appears to have affected visual performance in a more variable fashion, and this may have been because the light was not merely obscuring the visibility of the instruments but also interfering with visual motion processing.

While these findings could have resulted from a specific vulnerability to strobing illumination, however, they do not rule out an alternative explanation. It is also plausible that the strobing exposures impaired performance more than the continuous exposures simply because their higher peak power levels enabled them to obscure more of the HUD, not because they interfered with visual motion processing. Because the laser conditions were matched for cumulative energy delivery, the peak irradiance in the strobing condition was twice the power level for continuous exposures. While cumulative energy delivery initially seems a reasonable criterion for matching two sources that differ in their temporal display characteristics, it is not clear that it is the only appropriate criterion⁵. It remains possible that the strobing condition impaired performance more than the continuous condition because the more powerful glare source washed out more of the HUD when it was on, and the dark adaptation that occurred when it was off (between flashes) was insufficient to lower visual thresholds below those in the continuous condition. In this case, the effective scotoma would remain larger (and less of the HUD instrument would remain visible) in the strobing condition.

We have, then, two reasonable accounts for how our strobing laser source might have interfered with visual performance, namely: 1) The chopped source obscured the visual field and also interfered with visual motion; or 2) The chopped source obscured the visual field and was more effective because of its higher power and the persistence of adaptation effects (flashblindness) between flashes. Our findings that the strobing condition yielded less reliable, less consistent orientation control than the continuous condition are consistent with the first account and do not rule out the second. The next experiment in this project should distinguish between these accounts. To test whether visual motion is subject to a particular vulnerability from strobing lasers, the experiment will compare a continuous-exposure condition to a chopped-exposure condition whose cumulative energy delivery is less than that of the continuous condition. Specifically, if chopped exposures disrupt the orientation task more than continuous exposures whose fixed power level equals the *peak* strobing power level, this would suggest strongly that strobing laser light is indeed privileged in its potential to disrupt dynamic visual processing.

⁵ It is not always reasonable to assume that two different adapting fields with disparate duty-cycle and peak intensity characteristics will have similar adaptation effects just because they are matched for cumulative energy delivery (Hood & Finkelstein, 1986). In some cases, a short, intense adaptation field can raise visual thresholds more than a longer-duration, dimmer field that is matched for cumulative energy (Crawford, 1946).

CONCLUSION

This project demonstrated a cost-effective, medium fidelity virtual cockpit environment, which was used to measure the effects of a simulated laser threat on performance in a visual flight task. The virtual cockpit was shown to be an effective tool for measuring human performance effects resulting from laser glare. An empirical comparison was made between continuous and strobing laser exposure conditions matched for cumulative energy delivery. Findings indicated a need to examine further the potential threat from strobing lasers: Both laser conditions disrupted performance in a virtual flight task and this performance impairment was more serious in the strobing condition.

These findings may have occurred because strobing exposures pose a particular threat to visual motion processing, or alternatively because cumulative energy matching between conditions yielded greater visual masking from the more powerful strobing exposures. Future experiments will distinguish between these alternatives by comparing continuous and strobing conditions matched for peak power, not cumulative energy. If the strobing source is found to disrupt dynamic visual processing more than do similarly-configured continuous sources, further experiments will manipulate the temporal parameters governing the chopped presentations. The objective of these further manipulations will be to identify the power, repetition frequency, and duty cycle characteristics that are most threatening to visual spatial orientation and general visual performance in the cockpit. Enriching our body of knowledge in this area will improve safety for Air Force aircrew and also, given the increased use of lasers in outdoor entertainment, in civilian aviation.

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APPENDIX: Calculating the forcing functions and selecting the instability parameter.

At the start of each trial, the software calculated two pseudo-random forcing functions, one for pitch and one for roll. These functions were implemented after the model of Kenyon & Kneller (1993) and Flach et al. (1992), and their instantaneous values were added to each axis' rate of change as time histories. Each function comprised the sum of eleven different sinusoidal components, which were prime harmonics of a fundamental sinusoid with a frequency of .007324 Hz. The prime frequency multiples for the eleven components were 7, 13, 29, 37, 53, 73, 103, 149, 211, 293, and 419. The strength of the simulated gusts was set in the vehicle model by scaling all the components simultaneously. This was accomplished by specifying the maximum rotational speed that could be added to the vehicle model if all the gust components peaked simultaneously. Each component's amplitude was scaled according to its ordinal rank from the first (lowest-frequency) to the eleventh component. The amplitude of the first component was divided by one, that of the second by two, etc. The ratio of the amplitude of the n th component (which we may call g_n) to the maximum gust value (which we may call G) was determined by the equivalent ratio of $1/n$ to the sum $(1/1 + \frac{1}{2} + \dots + 1/11)$, according to the equation

$$\frac{(1/n)}{(1/1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{11})} = g_n / G$$

Thus if a maximum gust value G of 10 deg/s were specified and we wanted to determine the amplitude g_2 of the second frequency component, we would use the ratio

$$\frac{(1/2)}{(1/1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{11})} = \frac{\frac{1}{2}}{3.02} = g_2 / 10$$

so g_2 would equal 1.66 deg/s. This scaling of components' amplitude according to their frequency caused the oscillations of the lower-frequency components to buffet the vehicle model through greater angles than higher-frequency components. This approximates the behavior of many real-world dynamic systems in which lower-frequency mechanical resonances, ocean waves, or wind gusts generally cause longer, deeper, or wider excursions. The global peak values that were applied in this experiment to the rotational disturbances in the pitch and roll axes were 11.4 deg/s and 24 deg/s, respectively.

The instability parameter λ was applied in both control axes. This value was the reciprocal of the time constant that determined how quickly the vehicle model toppled away from level orientation. The time constant is dynamically equivalent to the length of a vertical pole one is attempting to balance in his palm. This experimental task is a subcritical tracking task, meaning that the system's inherent instability remained constant over time. A λ value of .4 was used in both pitch and bank axes. This is a weak instability factor compared to those used in other studies involving sub-critical tracking (Kenyon & Kneller, 1993; Previc et al., 1993; Beer, Gallaway, & Previc, 1996); it was just sufficient to veer the vehicle model away from straight and level flight within the duration of the laser exposures.